STUDY ON THE CRITICAL CANCELLING SPEED FOR THE HORIZONTAL EMPENNAGE CONTROL IN A CANARD CONFIGURATION IN AN ATMOSPHERE WITH ASCENDING VERTICAL GUSTS

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Abstract **- This work is a study on the the critical cancelling speed for the horizontal empennage control in a canard configuration aircraft, in a hypothesis unfavourable to normal flight. The cumulated effect four fudelage elastic deformation (φ) is taken into account and so is the elevator deflection effect (β), the empennage arrow angle effect (χ) and the vertical ascending gusts effect (ω).**

Key words: *critical cancelling speed for the horizontal empennage control, vertical gusts effect, fuselage elastic deformation effect, elevator deflection effect.*

1. INTRODUCTION

Unlike other specialty literature [1,2], the cumulated effects of ascending vertical gusts and arrow angle are taken into consideration.

Considering these effects leads to an ample view of horizontal empennage control cancelling in a canard configuration aircraft. The paper's conclusions are useful to both designers – by providing concrete data for the aircraft dimensioning phase – and to pilots – by indicating the manner of flying the aircraft so as to avoid this extremely dangerous phenomenon.

2. DETERMINING CRITICAL DYNAMIC PRESSURE FOR THE CANCELLING OF HORIZONTAL EMPENNAGE CONTROL

Let's consider a canard type aircraft like in fig. 1.

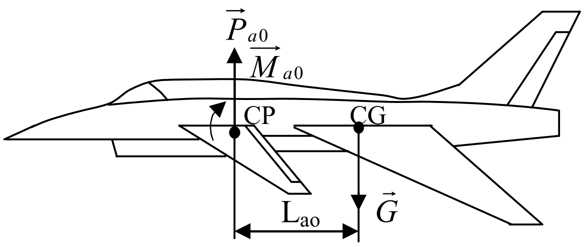

Fig.1

Using traditional notation, horizontal empennage lift in a canard configuration [3] comes from the formula:

$$P_{ao} = qS_{ao}\{\frac{dC_z}{d\alpha}[qS_{ao}(A+B)\pm\Delta\alpha]+C\} \quad (1)$$

where:

$$A=\frac{\frac{1}{K_1}\frac{dC_{zao}}{d\alpha}\Delta\alpha}{1-\frac{qS_{ao}}{K_1}\frac{dC_{zao}}{d\alpha}}$$

$$B=\frac{\frac{1}{K_1}\frac{dC_{zao}}{d\beta}+\frac{c_{ao}}{K_2}\frac{dC_{mao}}{d\beta}}{1-\frac{qS_{ao}}{K_1}\frac{dC_{zao}}{d\alpha}}\beta$$

$$C=\frac{dC_{zao}}{d\alpha}\beta$$

Finally, horizontal empennage lift comes from the formula:

$$P_{ao}=\frac{qS_{ao}}{1-\frac{qS_{ao}}{K_1}\frac{dC_{zao}}{d\alpha}}\left(\pm\frac{dC_{zao}}{d\alpha}\Delta\alpha+\frac{dC_{zao}}{d\beta}\beta+\frac{qS_{ao}c_{ao}}{K_2}\frac{dC_{ao}}{d\alpha}\frac{dC_{mao}}{d\beta}\beta\right) \quad (2)$$

The pitching moment created around the airship's center of gravity is:

$$M_{CG}=M_{ao}+P_{ao}\cdot L_{ao} \quad (3)$$

where L_{ao} is the aerodynamic length.

Finally the moment acting on the airship's center of gravity is obtained:

$$M_{CG}=qS_{ao}\{c_{ao}\frac{dC_{mao}}{d\beta}\beta+\frac{L_{ao}}{1-\frac{qS_{ao}}{K_1}\frac{dC_{zao}}{d\alpha}}\cdot [\pm\frac{dC_{zao}}{d\alpha}\frac{w}{V_0}+(\frac{dC_{zao}}{d\beta}+ +\frac{qS_{ao}c_{ao}}{K_2}\frac{dC_{ao}}{d\alpha}\frac{dC_{mao}}{d\beta})\beta]\} \quad (4)$$

The cancelling of elevator control on its deflection by the angle β in the presence of vertical gusts takes place if:

$$(1-\frac{q_cS_{ao}}{K_1}\frac{dC_{zao}}{d\alpha})c_{ao}\frac{dC_{mao}}{d\beta}\beta+L_{ao}\cdot$$

$$[(\frac{dC_{zao}}{d\beta}+\frac{q_cS_{ao}c_{ao}}{K_2}\frac{dC_{ao}}{d\alpha}\frac{dC_{mao}}{d\beta})\beta\pm\frac{dC_{zao}}{d\alpha}\frac{w}{V_0}]=0 \quad (5)$$

or

$$c_{ao}\frac{dC_{mao}}{d\beta}\beta+\frac{L_{ao}}{1-\frac{q_cS_{ao}}{K_1}\frac{dC_{zao}}{d\alpha}}\cdot$$

$$[\pm\frac{dC_{zao}}{d\alpha}\frac{w}{V_0}+(\frac{dC_{zao}}{d\beta}+$$

$$+\frac{q_cS_{ao}c_{ao}}{K_2}\frac{dC_{ao}}{d\alpha}\frac{dC_{mao}}{d\beta})\beta]=0 \quad (6)$$

$$c_{ao}\frac{dC_{mao}}{d\beta}\beta+(\frac{dC_{zao}}{d\beta}\beta\pm\frac{dC_{zao}}{d\alpha}\frac{w}{V_0})L_{ao}=$$

$$q_cS_{ao}\beta(\frac{c_{ao}}{K_1}\frac{dC_{zao}}{d\alpha}\frac{dC_{mao}}{d\beta}-$$

$$-\frac{L_{ao}}{K_2}c_{ao}\frac{dC_{ao}}{d\alpha}\frac{dC_{mao}}{d\beta}) \quad (7)$$

We obtain the critical dynamic pressure for control canclelling in the presence of horizontal empennage deflection:

$$q_c=\frac{c_{ao}\frac{dC_{mao}}{d\beta}\beta+(\frac{dC_{zao}}{d\beta}\beta\pm\frac{dC_{zao}}{d\alpha}\frac{w}{V_0})L_{ao}}{c_{ao}S_{ao}\beta(\frac{1}{K_1}-\frac{L_{ao}}{K_2})\frac{dC_{zao}}{d\alpha}\frac{dC_{mao}}{d\beta}} \quad (8)$$

If the arrow effect is considered, then[3]:

$$\left(\frac{dC_{zao}}{d\alpha}\right)_\chi=\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\cos\chi \quad (9)$$

where $\left(\frac{dC_{zao}}{d\alpha}\right)_\chi$ is the lift coefficient angle for the horizontal empennage with the arrow angle χ, $\left(\frac{dC_{aon}}{d\alpha_n}\right)_0$ is the lift coefficient angle for the horizontal empennage along the focus line perpendicular.

By accounting for the empennage's arrow angle we find that the critical dynamic pressure for control canclelling of the horizontal empennage is, in its final form:

$$q_c=$$

$$=\frac{c_{ao}\frac{dC_{mao}}{d\beta}\beta+[\frac{dC_{zao}}{d\beta}\beta\pm\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{w}{V_0}\cos\chi]L_{ao}}{c_{ao}S_{ao}\beta(\frac{1}{K_1}-\frac{L_{ao}}{K_2})\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{dC_{mao}}{d\beta}\cos\chi} \quad (10)$$

3. THE CRITICAL CANCELLING SPEED FOR HORIZONTAL EMPENNAGE CONTROL IN THE PRESENCE OF ASCENDING VERTICAL GUSTS

In this case the upper sign is considered in (10) and we obtain the critical pressure for deflection control cancelling on the horizontal empennage:

$$q_c=$$

$$=\frac{c_{ao}\frac{dC_{mao}}{d\beta}\beta+[\frac{dC_{zao}}{d\beta}\beta+\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{w}{V_0}\cos\chi]L_{ao}}{c_{ao}S_{ao}\beta(\frac{1}{K_1}-\frac{L_{ao}}{K_2})\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{dC_{mao}}{d\beta}\cos\chi} \quad (11)$$

or

$$q_c=K_2\times$$

$$\times\frac{\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\beta+\frac{dC_{zao}}{d\beta}\beta+\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{w}{V_0}\cos\chi}{c_{ao}S_{ao}\beta(\frac{K_2}{K_1L_{ao}}-1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{dC_{mao}}{d\beta}\cos\chi} \quad (12)$$

Considering the dynamic pressure $q_c=\frac{\rho}{2}\left(V_{ao}^2+w^2\right)$ we obtain

$$V_{ao}^2=\frac{K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1L_{ao}}-1)\frac{dC_{mao}}{d\beta}}\frac{w}{V_{a0}}-w^2+$$

$$+\frac{\left(\frac{dC_{zao}}{d\beta}\beta+\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1L_{ao}}-1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{dC_{mao}}{d\beta}\cos\chi} \quad (13)$$

Considering (13), the problem of the cummulated effects of ascending gusts and elastic fuselage deformation must be studied in the following disting cases:

1. $\frac{K_2}{K_1L_{ao}}-1\rangle 0$ and $\frac{dC_{zao}}{d\beta}\beta+\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\geq 0$;
2. $\frac{K_2}{K_1L_{ao}}-1\rangle 0$ and $\frac{dC_{zao}}{d\beta}\beta+\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\langle 0$;
3. $\frac{K_2}{K_1L_{ao}}-1\langle 0$ and $\frac{dC_{zao}}{d\beta}\beta+\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\geq 0$;
4. $\frac{K_2}{K_1L_{ao}}-1\langle 0$ and $\frac{dC_{zao}}{d\beta}\beta+\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\langle 0$;(14)
5. $\frac{K_2}{K_1L_{ao}}-1=0$.

1. $L_{ao}\langle\dfrac{K_2}{K_1}$ and $L_{ao}\geq\dfrac{\left|\dfrac{dC_{mao}}{d\beta}\right|}{\dfrac{dC_{zao}}{d\beta}}c_{ao}$;

2. $L_{ao}\langle\dfrac{K_2}{K_1}$ and $L_{ao}\langle\dfrac{\left|\dfrac{dC_{mao}}{d\beta}\right|}{\dfrac{dC_{zao}}{d\beta}}c_{ao}$;

3. $L_{ao}\rangle\dfrac{K_2}{K_1}$ and $L_{ao}\rangle\dfrac{\left|\dfrac{dC_{mao}}{d\beta}\right|}{\dfrac{dC_{zao}}{d\beta}}c_{ao}$; (15)

4. $L_{ao}\rangle\dfrac{K_2}{K_1}$ and $L_{ao}\langle\dfrac{\left|\dfrac{dC_{mao}}{d\beta}\right|}{\dfrac{dC_{zao}}{d\beta}}c_{ao}$

5. $L_{ao}=\dfrac{K_2}{K_1}$.

Case 1. This is incompatible with (14) because it involves the '-' sign in the left part of the equation and the '+' sign in the right part. Thus, the airship can fly at any speed and with any elevator deflection angle, with no consequence to horizontal empennage control. From this situation's conditions of existance we obtain:

$$\frac{K_2}{K_1}\rangle\frac{\left|\dfrac{dC_{mao}}{d\beta}\right|}{\dfrac{dC_{zao}}{d\beta}}c_{ao} \tag{16}$$

This is the case for a compact structure aircraft, with a small distance between horizontal emepennage's pressure center and the airship's center of gravity. The rigidity characteristics of fuselage structure are limited by the horizontal empennage's aerodynamic characteristics.

Case 2. In (14) the only positive term is the third. Let the left part of (14) be

$$g(V_{0crt})=V_{0crt}^2. \tag{17}$$

The right part of the same equality will be

$$h(V_{ocrt})=\frac{K_2}{\dfrac{\rho}{2}c_{ao}S_{ao}\beta(\dfrac{K_2}{K_1L_{ao}}-1)\dfrac{dC_{mao}}{d\beta}}\frac{w}{V_{0crt}}-w^2+$$
$$+\frac{\left(\dfrac{dC_{zao}}{d\beta}\beta+\dfrac{c_{ao}}{L_{ao}}\dfrac{dC_{mao}}{d\beta}\right)K_2}{\dfrac{\rho}{2}c_{ao}S_{ao}\beta(\dfrac{K_2}{K_1L_{ao}}-1)\left(\dfrac{dC_{zaon}}{d\alpha_n}\right)_0\dfrac{dC_{mao}}{d\beta}\cos\chi} \tag{18}$$

There are three possible subcases:

a)
$$-w^2+$$
$$+\frac{\left(\dfrac{dC_{zao}}{d\beta}\beta+\dfrac{c_{ao}}{L_{ao}}\dfrac{dC_{mao}}{d\beta}\right)K_2}{\dfrac{\rho}{2}c_{ao}S_{ao}\beta(\dfrac{K_2}{K_1L_{ao}}-1)\left(\dfrac{dC_{zaon}}{d\alpha_n}\right)_0\dfrac{dC_{mao}}{d\beta}\cos\chi}\rangle 0 \tag{19}$$

The functions $g(V_{0crt})$ and $h(V_{0crt})$ can be represented as in fig. 2, fig. 3 and fig. 4.

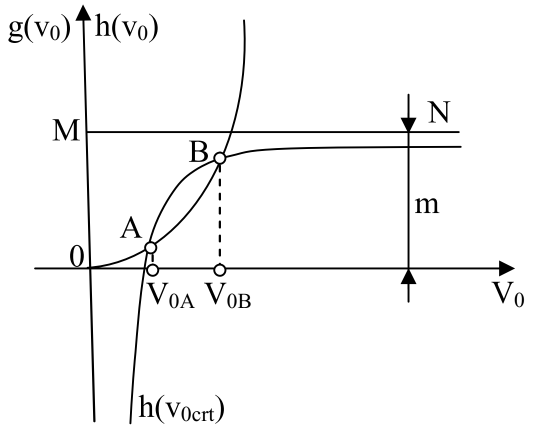

Fig.2

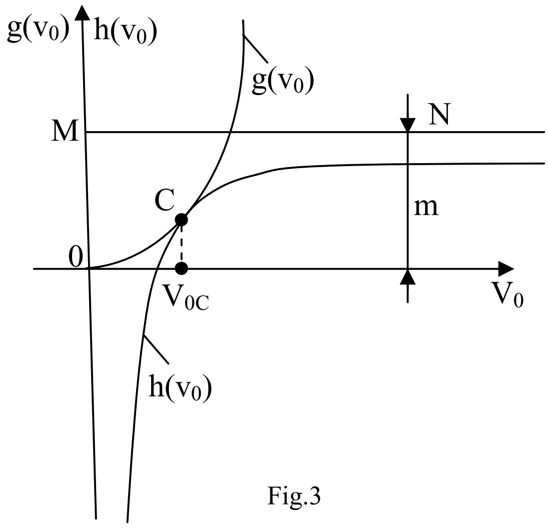

Fig.3

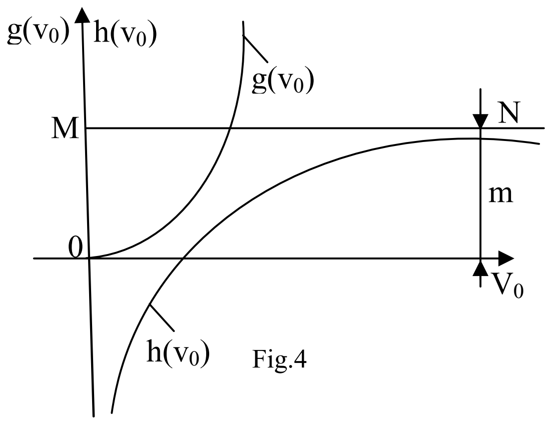

Fig.4

In fig. 2 the situation where the two curves intersect is represented. Two solutions result,
V_{0A} şi V_{0B} for whom horizontal empennage control is cancelled.
Fig. 3. represents the situation where the curves are tangent. From the condition that their angles in tangent point C are equal, V_{0C} - the critical horizontal empennage control cancelling speed is determined:

$$V_{0C}=\left(\frac{K_2}{\rho S_{ao}\left(\frac{K_2}{K_1 L_{ao}}-1\right)\left|\frac{dC_{mao}}{d\beta}\right|}\right)^{1/3} \tag{20}$$

In fig. 4. the curves $g(V_{0crt})$ şi $h(V_{0crt})$ have no common point. It is the situation where the airship can fly at any deflection angle and at any V_0 speed without horizontal empennage control cancelling.
From (19), the speed of the ascending gust is:

$$w\langle\sqrt{\frac{\left(\frac{dC_{zao}}{d\beta}\beta+\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1 L_{ao}}-1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{dC_{mao}}{d\beta}\cos\chi}} \tag{21}$$

For which, as shown before, there can be two, one or none flight speed at which there is without horizontal empennage control cancelling .
b)

$$-w^2+\frac{\left(\frac{dC_{zao}}{d\beta}\beta+\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1 L_{ao}}-1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{dC_{mao}}{d\beta}\cos\chi}=0 \tag{22}$$

The equation (22) allows for the immediate determination of gust speed

$$w=\sqrt{\frac{\left(\frac{dC_{zao}}{d\beta}\beta+\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1 L_{ao}}-1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{dC_{mao}}{d\beta}\cos\chi}} \tag{23}$$

For which this situation is possible.

From (14) the critical cancelling speed for horizontal empennage control is determined:

$$V_{0C}=\left[\frac{K_2}{\frac{\rho}{2}c_{ao}S_{ao}(\frac{K_2}{K_1 L_{ao}}-1)\frac{dC_{mao}}{d\beta}}w\right]^{1/3} \tag{24}$$

Thus, the airship may fly at any speed in an atmosphere with gusts of the intensity (23) if it meets the building conditions in (14), case 2.
c)

$$-w^2+\frac{\left(\frac{dC_{zao}}{d\beta}\beta+\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1 L_{ao}}-1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{dC_{mao}}{d\beta}\cos\chi}\langle 0 \tag{25}$$

The first term from the right side of (14) is also negative. This situation is thus physically unacceptable. Thus, the airship may fly at any speed in an atmosphere with gusts of the intensity (25) if it meets the building conditions in (14), case 2.
Case 3.
This case too will be studied according to ascending gust speed. There are two possible subcases:
a)

$$-w^2+\frac{\left(\frac{dC_{zao}}{d\beta}\beta+\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1 L_{ao}}-1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{dC_{mao}}{d\beta}\cos\chi}\rangle 0 \tag{26}$$

so

$$w\langle\sqrt{\frac{\left(\frac{dC_{zao}}{d\beta}\beta+\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1 L_{ao}}-1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0\frac{dC_{mao}}{d\beta}\cos\chi}} \tag{27}$$

We note by m left member of (26).
The functions $g(V_{0crt})$ and $h(V_{0crt})$ can be represented as in fig. 5:

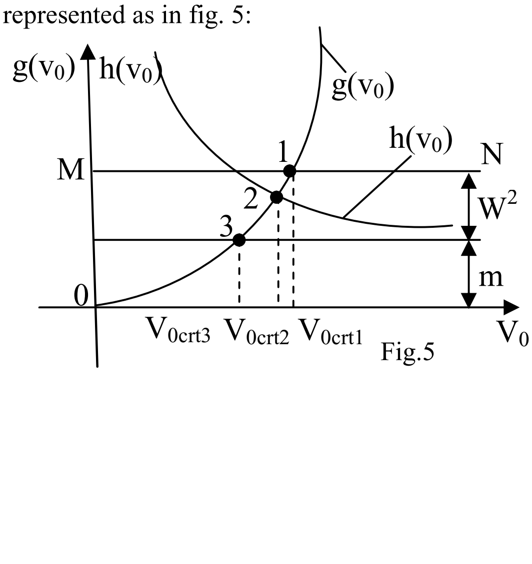

Fig.5

In fig. 5 there are three distinct points.

-Point 1, corresponding to the situation where the airship flies in a quiet atmosphere, with no gusts. By introducing in (13) $w = 0$ the critical cancelling speed for horizontal empennage control is determined:

$$V_{0crt1} = \sqrt{\frac{\left(\frac{dC_{zao}}{d\beta}\beta + \frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1 L_{ao}} - 1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0 \frac{dC_{mao}}{d\beta}\cos\chi}} \tag{28}$$

-Point 2, where the airship is in a real atmosphere, with vertical gusts. For $g(V_{0crt}) = h(V_{0crt})$ the critical cancelling speed for horizontal empennage control V_{0crt2} is obtained.

-Point 3 represents the hypothetical situation where the airship flies with infinite speed in the presence of ascending gusts. The critical cancelling speed for horizontal empennage control comes from (13):

$$V_{0crt3} = \sqrt{\frac{\left(\frac{dC_{zao}}{d\beta}\beta + \frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1 L_{ao}} - 1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0 \frac{dC_{mao}}{d\beta}\cos\chi} - w^2} \tag{29}$$

b)

$$-w^2 + \frac{\left(\frac{dC_{zao}}{d\beta}\beta + \frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1 L_{ao}} - 1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0 \frac{dC_{mao}}{d\beta}\cos\chi} = 0 \tag{30}$$

The gust's speed comes from (30):

$$w = \sqrt{\frac{\left(\frac{dC_{zao}}{d\beta}\beta + \frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2}{\frac{\rho}{2}c_{ao}S_{ao}\beta(\frac{K_2}{K_1 L_{ao}} - 1)\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0 \frac{dC_{mao}}{d\beta}\cos\chi}} \tag{31}$$

And from (13) we obtain:

$$V_{0crt} = \left[\frac{\left(\frac{dC_{zao}}{d\beta}\beta + \frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\right)K_2^3}{\frac{\rho^3}{8}c_{ao}^3 S_{ao}^3\beta^2(\frac{K_2}{K_1 L_{ao}} - 1)^3\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0 \left(\frac{dC_{mao}}{d\beta}\right)^3\cos\chi}\right]^{1/6} \tag{32}$$

<u>Case 4.</u>

The functions $g(V_{0crt})$ şi $h(V_{0crt})$ are represented like in fig. 6.

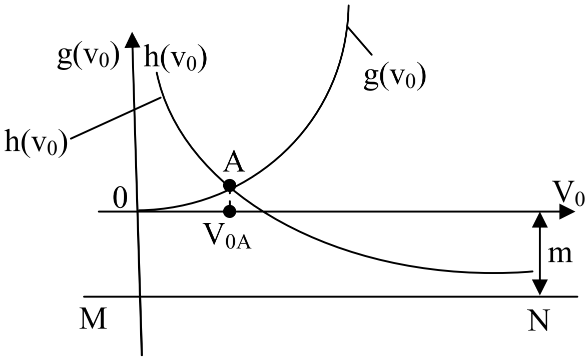

Fig.6

From the graphical representation we obtain that there is only one critical cancelling speed for horizontal empennage control -V_{0A}.

<u>Case 5.</u>

This is the limit case for a compact structure

(7) becomes:

$$c_{ao}\frac{dC_{mao}}{d\beta}\beta + (\frac{dC_{zao}}{d\beta}\beta \pm \frac{dC_{zao}}{d\alpha}\frac{w}{V_{0crt}})L_{ao} = 0 \tag{33}$$

Equation (33) allows the determining of the critical cancelling speed for horizontal empennage control:

$$V_{0crt} = -\frac{w\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0 \cos\chi}{\frac{c_{ao}}{L_{ao}}\frac{dC_{mao}}{d\beta}\beta} \tag{34}$$

Because $\frac{dC_{mao}}{d\beta} \langle 0$, (34) can be written as:

$$V_{0crt} = \frac{\left(\frac{dC_{zaon}}{d\alpha_n}\right)_0 \cos\chi}{\left|\frac{dC_{mao}}{d\beta}\right|}\frac{wL_{ao}}{c_{ao}\beta} \tag{35}$$

4. CONCLUSIONS

1. The canard airship must be designed according to the conditions in case 1, by respecting (16). In this situation the airship will have a compact structure, resitant to the cumulative action of fuselage elasticity and ascending vertical gusts, no matter their w speed;
2. Increasing the arrow angle χ leads to an increase of the cancelling speed for horizontal empennage control;

3. Increasing the deflection angle β leads to a decrease of the cancelling speed for horizontal empennage control;
4. Increasing S_{ao} and c_{ao} leads to small critical cancelling speeds for horizontal empennage control;
5. Because at greater heights air density ρ is smaller, flying at higher altitudes is recommended;
6. According to the canard airship's purpose (fighting or transportation) the building variant can be chosen from the design stage, according to the 5 cases that were previously studied.

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